

Discovery of Charged Higgs through $\gamma\gamma$ final states

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Abstract

Extending the Higgs sector by an additional $SU(2)_L$ doublet Higgs boson implies the existence of a charged Higgs boson H^+ . The LHC experiments search for such particle focusing on its decays into leptonic and quark decay final states, namely $\tau\nu, cs$ and tb . However, if the Higgs sector is further extended, e.g. by a gauge singlet as in the NMSSM, the charged Higgs boson can also decay into a light scalar or pseudoscalar Higgs boson which itself decays further into a two photon final state. We present here scenarios where H^+ is produced in top-quark decays with a sizable cross-section such that the corresponding signal is well above the Standard Model background at the 13 TeV run of the Large Hadron Collider (LHC) with an integrated luminosity 100 fb^{-1} .

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I. INTRODUCTION

The discovery of a scalar particle at the LHC which resembles strongly the Higgs particle of the Standard Model (SM) with $m_H \sim 125\text{GeV}$ [1, 2] has been a great stride so far. Even though this particle shares many of the properties of the SM Higgs boson, it could still be a member of an extended Higgs sector, see e.g. [3] and references therein. The search for the corresponding additional particles as well as for deviations in the properties of the Higgs boson (see e.g. [4]) is one of the major tasks of the LHC experiments [5].

A particular well studied class of models are supersymmetric extensions of the SM. In its minimal version the Higgs sector is a two Higgs doublet model of type II. However, there are several other possibilities where the simplest one is adding a gauge singlet Higgs field. An extended Higgs sector also implies non-standard production and decay possibilities, in particular for the additional Higgs particles. In case of the Next to Minimal Supersymmetric Standard Model (NMSSM) [6, 7] a challenging task will be to find the additional states which resemble mainly the gauge singlet ones (see e.g. [8]). As the direct production is strongly suppressed, one can use for example cascade decays of supersymmetric particles or heavier Higgs bosons to produce them [9–15]. Similarly, pair production of the lighter Higgs bosons can be potentially a very interesting probe [16–20]. Additionally, the singlet scalar could also open up new avenues to search for the charged Higgs scalar at the LHC e.g. via the cascade decays of the top quark, $t \rightarrow H^+ b \rightarrow W^+ \Phi b \rightarrow W^+ b f \bar{f}$ [21] where $\Phi = H_1(A_1)$ is the lightest (pseudo)scalar Higgs boson [21] and $f = b, \tau, \mu$ depending on the kinematical thresholds. A light pseudo-scalar A_1 decaying into $\tau^+ \tau^-$ has been searched for by CDF [22] and bounds have been set for masses of about 9 GeV. In the context of LHC, it has been shown recently that the aforementioned scenarios can easily be probed either with existing data or in the future runs [23, 24]. In addition the process $pp \rightarrow H_3 \rightarrow W^\pm H^\mp$ has been considered [25] with the subsequent decay of H^\mp into H_1 , where H_3 is the heaviest scalar Higgs boson.

In this letter we investigate to which extent the charged Higgs boson can still be produced via top-quark decays with a subsequent decay of the latter into a light Higgs boson (H_1 or A_1). We will focus on an intermediate mass range of the scalar and pseudoscalar of about

60-80 GeV which is potentially challenging since the main decay modes are a pair of gluons and/or charm/bottom quark pair. However, there is the possibility of an enhanced rate for $\gamma\gamma$ in this mass range as we will show below. Final states resulting from $t\bar{t}$ production and containing two photons have a rather small cross-sections in the SM and, thus, we find excellent prospects for the discovery of new physics in the next run at the LHC for scenarios where H^\pm decays dominantly into W^+H_1/A_1 .

In the next section we will briefly summarize the main features of the Higgs sector of the NMSSM and in section III two examples are presented. We will demonstrate how a charged Higgs boson as well as a light Higgs boson can be discovered at the LHC using Monte Carlo studies. In section IV we will draw our conclusions.

II. THE HIGGS SECTOR OF THE NMSSM AND SOME PHENOMENOLOGICAL ASPECTS

In this section we briefly summarize some main features related to the NMSSM Higgs sector. The superpotential of the NMSSM can be specified as

$$W_{NMSSM} = \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 + W_{MSSM} \quad (1)$$

where W_{MSSM} refer to the Yukawa interactions of the matter fields with the Higgs doublets already present in the MSSM. The vacuum expectation value (vev) s of the real scalar component of S generates an effective μ -term

$$\mu_{eff} = \lambda s. \quad (2)$$

Moreover, the Lagrangian of the NMSSM contains trilinear and bilinear soft SUSY breaking terms related to the singlet Higgs sector:

$$-\mathcal{L}_{NMSSM}^{Soft} = m_S^2 |S|^2 + \left(\lambda A_\lambda H_u \cdot H_d S + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.} \right) + \dots; \quad (3)$$

where, ... refers to the soft SUSY breaking terms already present in the MSSM. The complete Higgs sector consists of

- 3 CP-even neutral Higgs bosons H_i , $i = 1, 2, 3$;

- 2 CP-odd neutral Higgs bosons A_1 and A_2 ;
- One charged Higgs boson H^\pm .

where the neutral sectors are admixtures of doublet and singlet Higgs fields.

The 2×2 mass matrix for the CP-odd Higgs bosons \mathcal{M}_P^2 has in the basis (A_{MSSM}, S_I) the elements

$$\begin{aligned}\mathcal{M}_{P,11}^2 &= \frac{2\mu_{\text{eff}}(A_\lambda + \kappa s)}{\sin 2\beta}, \\ \mathcal{M}_{P,22}^2 &= \lambda(A_\lambda/s + 4\kappa)v_u v_d - 3\kappa A_\kappa s, \\ \mathcal{M}_{P,12}^2 &= \lambda(A_\lambda - 2\kappa s)v\end{aligned}\tag{4}$$

where v_u, v_d denote the vevs of H_u, H_d , respectively, $v = \sqrt{v_u^2 + v_d^2}$ and, as usual, $\tan \beta = v_u/v_d$. The entry $\mathcal{M}_{P,11}^2$ would resemble the mass of the MSSM-like CP-odd scalar. Note, that the singlet like-state can be relatively light. We order the mass eigenstates according to $m_{A_1} \leq m_{A_2}$ and apply this also to the scalar sector.

In the CP-even sector, three states $H_i (i = 1, 2, 3)$ are admixtures of the real components H_u, H_d and S . The state H_{SM} , which could be either H_1 or H_2 , with the nearly SM-like coupling to the electroweak gauge bosons has a mass [26, 27]

$$m_{H_{SM}}^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{radcorrs} + \Delta_{\text{mix}} \quad .\tag{5}$$

The term Δ_{mix} represents the singlet-doublet mixing

$$\Delta_{\text{mix}} \simeq \frac{4\lambda^2 s^2 v^2 (\lambda - \kappa \sin 2\beta)^2}{\overline{M}_{H_{SM}}^2 - M_S^2}\tag{6}$$

where $\overline{M}_{H_{SM}}^2$ is $m_{H_{SM}}^2$ without the mixing term and M_S^2 is the mass of singlet like Higgs boson. In scenarios as considered here where all Higgs states are light enough, one can still have significant mixing among all these states. If the singlet like state M_S^2 is lighter/heavier than $\overline{M}_{H_{SM}}^2$, then Δ_{mix} can even produce significant positive/negative contributions to the lightest Higgs state.

The mass of the charged Higgs scalar is given by

$$M_{H^\pm}^2 = M_A^2 + v^2 \left(\frac{g_2^2}{2} - \lambda^2 \right).\tag{7}$$

Clearly, it decreases with increasing λ . We stress that even if this discussion of the masses is mainly at tree-level, we have included the complete one-loop corrections to the Higgs masses [28–30] and the dominant two-loop corrections [28] in the numerical examples below.

The phenomenology of H^+ can differ significantly within the NMSSM compared to the MSSM, as it can potentially decay into the $W^+H_1(A_1)$ even if its mass is below the t -quark mass. The latter will decay further into $f\bar{f}$, gg and $\gamma\gamma$ pairs. It turns out that small values of $\tan\beta$ are preferred as both $BR(t \rightarrow bH^\pm)$ and $BR(H^\pm \rightarrow W^\pm H_1(A_1))$ are enhanced in this case [24]. As mentioned in the introduction we are particularly interested in H_1 and/or A_1 in the mass range of 60–80 GeV where the lower bound is given by the requirement that the SM-like Higgs boson should not decay dominantly into two lighter Higgs bosons. It has recently been shown that such a light A_1 can be tested with the existing LHC data [23] if it decays dominantly into $b\bar{b}$ with a branching ratio of about 90%. As we will show, the $\gamma\gamma$ channel can also be an interesting probe in this case. Similarly, for small $\tan\beta$ the lightest CP-even Higgs scalar H_1 , which is mainly a singlet-like state, can dominantly decay into gluon pairs and/or charm quark pairs if the residual H_u component is more important than the residual H_d component. Both channels do not offer much prospects at the LHC. However, the decay into two photons can be enhanced if the chargino is light [31–33] and in case of H_1 this can be further enhanced by a light H^+ . Clearly, such light states are also subject to flavour constraints as we will discuss below.

III. BENCHMARK SCENARIOS

For the numerical evaluation we use **SARAH** [34–38] to generate a NMSSM version of **SPheno** [39, 40] to compute the Higgs and the SUSY particle spectrum, along with various couplings, decay widths, and branching ratios. For the calculation of flavour observables we use the package **FlavorKit** [41]. The spectrum is calculated including the complete one-loop corrections for all masses of supersymmetric particles and Higgs bosons [28, 29] and as well the dominant two-loop radiative corrections for Higgs bosons [28].

The numerical examples below we have taken $m_t = 173.1$ GeV. Moreover, they are compatible with the following constraints:

- Squark masses except for stops and sbottoms are assumed to be around ~ 1.5 TeV to alleviate LHC constraints from direct SUSY searches [42, 43]. For the same reason we assume the gluino mass $m_{\tilde{g}}$ to be larger than 1.6 TeV. In case of third generation squarks, the ATLAS [44–49] and CMS collaborations [50, 51] have obtained a limit of up to 750 GeV for $m_{\tilde{t}_1}$ assuming a 100% branching ratio into either $\tilde{t}_1 \rightarrow t\chi_1^0$ or $\tilde{t}_1 \rightarrow b\chi_1^\pm$. However, it has been shown that these bounds are relaxed if multiple final states are possible at the same time [52, 53]. As this is the case for our parameter choices below we take a lower bound of 600 GeV for $m_{\tilde{t}_1}$.
- A SM-like Higgs boson with a mass in the range $M_{H_{SM}} = 123 - 128$ GeV. For this we have fixed the trilinear soft susy breaking terms to: $T_{b,\tau} = A_{b,\tau}y_{b,\tau} = -1$ TeV and $T_t = A_t y_t = -2.8$ TeV. Moreover, we check that the Higgs sector is consistent with existing data by using HiggsBounds-4.1.1 [54, 55].
- The first two generations of slepton masses are assumed to be around 200 GeV to have consistent spectra with the muon anomalous magnetic moment constraint. However, for our considerations below it does not matter if they are heavier.
- It is quite well known that a light H^\pm can lead to potentially large contributions to flavor physics observables. The most constraining ones are $BR(b \rightarrow s\gamma) = (3.43 \pm 0.21 \pm 0.07 \pm 0.24^{th}) \times 10^{-4}$ [56–58], $\Delta M_{B_s} = 17.69 \pm 0.08 \pm 3.3^{th}$ ps $^{-1}$ [58, 59], $\Delta M_{B_d} = 0.507 \pm 0.004 \pm 0.091^{th}$ ps $^{-1}$ [58, 59] and $BR(B_s \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7 \pm 0.29^{th})10^{-9}$ [60–62]¹. In the context of NMSSM, these constraints were studied in detail in [63]. In the region of the parameter space where $\tan\beta$ is small, the branching ratio $BR(B_s \rightarrow \mu^+\mu^-)$ can easily be satisfied. However, the other three constraints are rather restrictive and we get values which are about 35-55% enlarged compared to the experimental values. They can be brought to consistent values within the experimental and theoretical uncertainties if one allows for small non-minimal flavour violating structures in the soft-SUSY breaking mass parameters as has been shown for example in [64–66] in the MSSM context with hardly an impact on the here discussed signatures. The flavour mixing parameters impact on the mass of the

¹ We considered 2013 web updated results from the <http://www.slac.stanford.edu/xorg/hfag/>

SM-like Higgs boson [67] but consistency between the Higgs mass constraint and the b -physics requirements can be achieved in a sizeable part of the parameter space [68].

We do not consider dark matter constraints in this work. Though the thermal relic abundance can be satisfied by tuning the values of M_1 , M_2 , μ and the slepton mass parameters, the limits from direct detection experiments on the dark matter can be very stringent, thanks to the substantial Higgsino component in lightest neutralino and lightness of all Higgs states in our examples. It is well-known that tuning the strange quark content of the nucleon [69] and exploiting the astro-physics uncertainties, the direct detection limits can be relaxed by $\mathcal{O}(10)$ [70]. Moreover, one can easily extend the model to include R -sneutrinos which could be the lightest SUSY particles. This can change the dark matter phenomenology significantly without affecting the discussion below, see e.g. [71–76].

In the table I we present two benchmark points BMP-A and BMP-B where the charged Higgs boson is lighter than the top quark. In both cases we consider t -quark pair production where one of t -quarks decays as usual into Wb whereas the second one decays into $H^+b \rightarrow \Phi Wb \rightarrow \gamma\gamma Wb$ as depicted in Fig. 1. Here Φ is either H_1 (scenario BMP-A) or A_1 (scenario BMP-B). We focus on the $\gamma\gamma$ decay mode of Φ due to its clean signature at the LHC. Before continuing we note that in the first case the decay $\Phi \rightarrow b\bar{b}$ is suppressed as H_1 is mainly a gauge singlet with a still sizeable H_u component which not only gives the relatively large branching ratio into $\gamma\gamma$ but also large branching ratios into $c\bar{c}$ and gg .

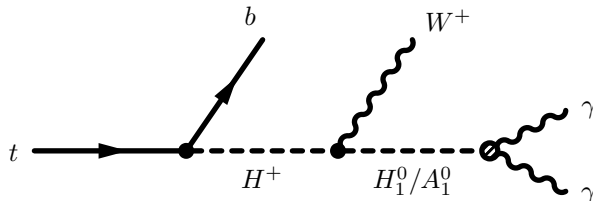


FIG. 1. Feynman diagram depicting cascade production of two photons from top decay via Higgs bosons.

parameter	BMP-A	BMP-B	Branching ratios	BMP-A	BMP-B
$\tan \beta$	1.68	1.45	$Br(t \rightarrow bH^+)$	3.3×10^{-3}	1.8×10^{-2}
κ	0.596	0.94	$Br(H^+ \rightarrow W^+ H_1)$	0.68	0
λ	0.596	0.62	$Br(H^+ \rightarrow W^+ A_1)$	0	0.86
μ_{eff}	131.5	143.7	$Br(H_1 \rightarrow \gamma\gamma)$	6.0×10^{-3}	1.76×10^{-3}
$m_{H_1^0}$	73.8	126.8	$Br(A_1 \rightarrow \gamma\gamma)$	2.6×10^{-5}	1.0×10^{-4}
$m_{H_2^0}$	126.7	172.0	$Br(H_1 \rightarrow b\bar{b})$	0.24	0.72
$m_{H_3^0}$	192.6	364.1	$Br(A_1 \rightarrow b\bar{b})$	0.11	0.86
$m_{A_1^0}$	155.4	66.6	$Br(H_1 \rightarrow c\bar{c})$	0.32	0
$m_{A_2^0}$	428.4	402.0	$Br(A_1 \rightarrow c\bar{c})$	0	0
m_{H^\pm}	161.9	149.4	$Br(H_1 \rightarrow g\ g)$	0.4	0.02
$m_{\tilde{t}_1}$	645.4	656.2	$Br(A_1 \rightarrow g\ g)$	0	0.02
$m_{\tilde{b}_1}$	883.5	879.0			

TABLE I. Relevant masses and branching fractions of the benchmark points used for our simulation. All masses are in GeV.

$p_{T_{min}}(j)$	$p_{T_{min}}(\gamma)$	$p_{T_{min}}(\ell)$	$ \eta _{max}(j)$	$ \eta _{max}(\gamma)$	$ \eta _{max}(\ell)$	ΔR
20 GeV	10 GeV	10 GeV	5	2.5	2.5	0.4

TABLE II. The default cut setup in MadGraph 5.1.5.13 where p_T is the transverse momentum, η the pseudorapidity and ΔR for the angular distance between two objects comprised of leptons, jets and photons.

We consider first the cross-section for the signal

$$\sigma_{2b+2W+2\gamma}^\Phi = 2 \times \sigma(pp \rightarrow t\bar{t}) \times Br(t \rightarrow bH^+) \times Br(\bar{t} \rightarrow \bar{b}W^-) \times Br(H^+ \rightarrow W^+\Phi) \times Br(\Phi \rightarrow \gamma\gamma) \quad (8)$$

with $\Phi = H_1, A_1$. For a qualitative understanding we calculate the effective signal events, as defined by $\mathcal{S}^{H_1(A_1)} \equiv \sigma_{2b+2W+2\gamma}^{H_1(A_1)} \times \mathcal{L}$, where \mathcal{L} represents the integrated luminosity for present or future LHC runs. The results are shown in Tab. III which have been calculated

CM energy	$\mathcal{L}(fb^{-1})$	BMP-A ($\mathcal{S}_{2b+2W+2\gamma}^{H_1}$)	BMP-B ($\mathcal{S}_{2b+2W+2\gamma}^{A_1}$)
8 TeV	20	121	14
13 TeV	100	1987	228
14 TeV	100	2351	270

TABLE III. Total signal events $\mathcal{S}_{2b+2W+2\gamma}^{H_1(A_1)}$ using leading order $\sigma(pp \rightarrow t\bar{t})$.

Background events	8 TeV	13 TeV	14 TeV
$pp \rightarrow W^+W^-b\bar{b}\gamma\gamma$	181	2859	3353
$pp \rightarrow W^+W^- \overset{(-)}{b} j\gamma\gamma$	5	146	261
$pp \rightarrow W^+W^- \overset{(-)}{b} \gamma\gamma$	9	194	240

TABLE IV. Number of the different SM background events without the subsequent decays of the W bosons using the default cuts given in Tab. II.

with MadGraph 5.1.5.13 [77] using its default cut setup as shown in Tab. II and with the CTEQ6L1 PDF set. These numbers have of course to be compared with the SM background processes. The dominant one is obviously the irreducible one: $pp \rightarrow WWb\bar{b} + \gamma\gamma$. In addition there are two more due to the fact that b -jet coming from the $t \rightarrow H^+b$ is rather soft due to the small mass difference $m_t - m_{H^+}$: (1) For $10 \text{ GeV} < p_T(b) < 25 \text{ GeV}$, where $p_T(b)$ is the transverse momentum of the b -jet, the b -jet can be reconstructed as a jet but its flavour cannot be identified anymore. The corresponding background is $WWbj + \gamma\gamma$. (2) For $p_T(b) < 10 \text{ GeV}$, the jet cannot be reconstructed at all and, thus, we take also $WWb + \gamma\gamma$ as a background into account. The cross-sections for all three background reactions are given in Tab. IV Comparing both tables we see that in the first scenario already a trivial counting of the events without any further cuts gives a clear indication that there is physics beyond the SM involved as the numbers for the signal and the background are of the same size.

In case of scenarios like BMP-B one needs of course further cuts to extract the corresponding signal. We have performed Monte Carlo studies for both scenarios at the parton level for this channel at the LHC with 13 TeV c.m.s. energy and assuming an integrated

$p_T(j)$	$m_{\gamma\gamma}$	p_T of hardest b	$p_T(\gamma)$	Δ_W^{jj}	ΔR_{min}
20 GeV	10 GeV	> 40 GeV	20 GeV	20 GeV	0.4

TABLE V. Cuts used for our simulation. The minimum p_T for jets has to be larger than 20 GeV for the two hardest jets and larger than 10 GeV for the softer ones. At least one of the two b quarks must have a $p_T > 40$ GeV. The invariant mass of the two hardest non-btagged jets is required to fulfil $|m_{jj} - m_W| < \Delta_W^{jj}$. The invariant mass of the two photons $m_{\gamma\gamma}$ has to be larger than 10 GeV. The photons need to have a $p_T > 20$ GeV.

luminosity of 100 fb^{-1} . For the signal process with one t decaying as depicted in Fig. 1 we use an implementation of the NMSSM to MadGraph that has been obtained from SARAH via the SUSY toolbox [78]. The $H_1^0/A_1^0 \rightarrow \gamma\gamma$ process is performed with Pythia [79]. The background processes are generated with MadGraph. We have generated 10^4 events for the signal of the aforementioned benchmark points and its background processes from Tab. IV assuming that one of the W 's decays hadronically and the other one leptonically to e or μ . We weight the generated events according to the cross-sections.

In Fig. 2 and Fig. 3 we plot the distribution of the invariant mass $m_{\gamma\gamma}$ of the 2-photon system for the signal and background processes using the cuts of Tab. V. We check that all identifiable objects, i.e. everything except the non-identifiable soft b jets, are well separated from each other with $\Delta R > 0.4$ and have $|\eta| < 2.5$. We demand that the two hardest jets with $p_T > 20$ GeV have an invariant mass m_{jj} within a window of $\Delta_W^{jj} = 20$ GeV around the W mass. Then we require two photons with $p_T > 20$ GeV and an invariant mass $m_{\gamma\gamma}$ of at least 10 GeV. Finally we demand one lepton with $p_T > 10$ GeV and that the hardest b has $p_T > 40$ GeV. As has to be expected from the above considerations one sees a clear signal peak over the background for the scenario BMP-A in Fig. 2. In case of BMP-B one sees in Fig. 3 that at least at the parton-level one has a clear signal over the background. However, in this case a full detector study will be necessary to check if this still holds under more realistic assumptions.

Last but not the least we want to stress, that all results have been obtained so far using tree-level cross-sections. However, it is well known that the $t\bar{t}$ production cross-sections receives

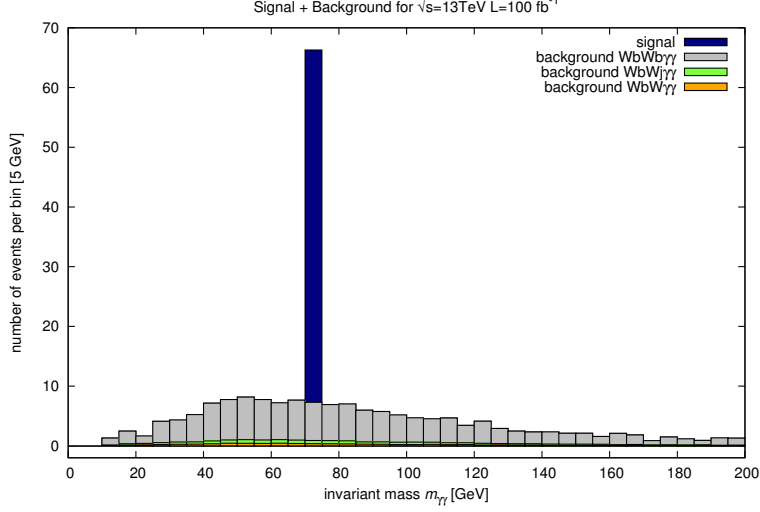


FIG. 2. Invariant mass distribution of the photon pair for BMP-A of signal (blue) and background contributions stemming from $pp \rightarrow W^+ b W^- \bar{b} \gamma \gamma$ (grey), from $pp \rightarrow W^+ b^{(-)} W^- j \gamma \gamma$ (green) and from $pp \rightarrow W^+ b^{(-)} W^- \gamma \gamma$ (orange) with one W decaying hadronically and the other one leptonically.

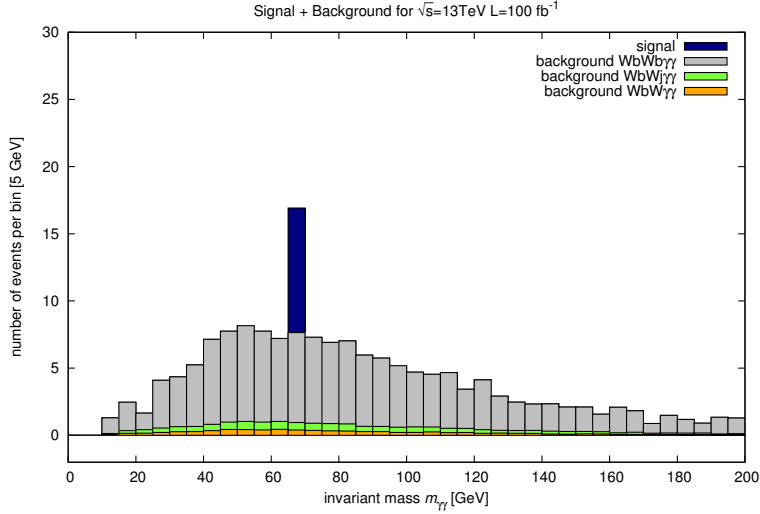


FIG. 3. Same as in Fig. 2, but for BMP-B.

large QCD corrections. Using the online-program available at ref. [80] we have calculated the top pair production cross-section $\sigma(pp \rightarrow t\bar{t})$ including NLO+NNLL corrections [81]. Here we have taken for $m_t = 173.1$ GeV and the PDF-set MSTW2008nnlo68cl [82]. Compared to the tree-level results used above we obtain a K-factor of 1.7, 1.6 and 1.6 for LHC 7, 13

and 14 TeV c.m.s. energy, respectively. In case that the background could be rescaled by a similar factor, this would imply an improvement of the signal over square root background ratio of about 30%.

Channel:	8 TeV	13 TeV	14 TeV
σ [fb]	228×10^3	746×10^3	882×10^3
σ_{LO-MG5} [fb]	135×10^3	463×10^3	555×10^3

TABLE VI. Signal cross-sections for $\sigma(pp \rightarrow t\bar{t})$ given in NLO+NNLL accuracy and at leading order according to MadGraph.

IV. CONCLUSIONS

Within the framework of the NMSSM the charged Higgs boson can dominantly decay into the lightest Higgs scalar Φ ($\Phi = H_1, A_1$) through $H^\pm \rightarrow W^\pm \Phi$. Subsequently, the lightest Higgs scalar can decay into $\gamma\gamma$ which leads to a novel channel for the discovery of H^\pm at the LHC. We have demonstrated this for two scenarios with $m_\Phi \in 60 - 80$ GeV. Our simulations at the parton-level delineate the clear excess of signal events over the backgrounds in the considered mass range of m_Φ which can easily be seen at the next runs of LHC. This will endorse the presence of a light Higgs scalar and a light charged Higgs boson of an extended Higgs sector in a supersymmetric framework. Thus LHC collaborations should expand their search strategy to include the di-photon search channel for a light charged Higgs scalar to account for this possibility. Last but not the least we note that the existence of such a light charged Higgs boson necessitates a non-trivial flavour structure in the squark sector to obtain consistency with the existing low energy data.

Acknowledgments

We thank G. Siragusa for discussions on b-tagging at the ATLAS experiment. This work has been supported by DFG, project no. PO-1337/3-1 and by DFG research training group GRK 1147. LM acknowledges support from the Elitenetzwerk Bayern.

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